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A Concise Guide to Detection of Tornadoes through the Anticipation of their Potential: An Aid to Better Forecasting

Much time and money has been invested in recent decades to enable better detection of tornadic storms, and thereby, improve tornado forecasting methods. A thorough knowledge of the types of atmospheric conditions from which a tornado can be produced is the key to such better detection and forecasting of tornadic events. Key to such prediction is an identification of the conditions which favor and enhance tornado potential. “Present-day operational tornado forecasting can be thought of in two parts: anticipation of tornadic potential in the storm environment and recognition of tornadic storms once they develop.”[1] Thus, it can be inferred that without a knowledge of what conditions favor the development of tornadoes, it is impossible to accurately recognize a tornadic storm before it occurs. This writing will serve as a guide to familiarize one with the atmospheric conditions likely for tornado formation, as well as give a brief history of advancements made in tornado forecasting. Useful radar methods for forecasting of tornadoes and their advantages and shortcomings will also be presented.

Despite tornado forecasting having its roots in the 1800s, it was not until the early 1950s that the serious forecasting of tornadoes began.[1] Up until that time, “the word ‘tornado’ in public forecasts was prohibited, largely because of the perception that tornado forecasts would cause public panic.”[1] When the recognition that preservation of life seemingly overweighed the concern over mass hysteria, true advancements in the research of the ominous tornado seemed to coincide. Despite the technological advancements of the computer (and later radar imagery), the forecasting of tornadoes seemed to rely empirically on “observed meteorological elements, such as static instability, significant extratropical cyclones, abundant low-level moisture, jet streams, surface convergence boundaries, and so forth.”[1] This period was one in which certain meteorological conditions, or “collection of elements,” came to form the basis for forecasting. "Weather radars were a brand-new technology, and no scientific basis existed to use a radar for understanding tornadic storms, much less detecting them when present."[1] Where tornado research began using the new technology to aid in understanding, the operational end of forecasting relied solely on the association of common collection of elements previously mentioned. It was not until the mid-1970s that "numerical cloud modeling had become capable of fully, three-dimensional, time-dependent storm simulations."[1] This could be pointed to as the timeframe, as Doswell and Johns have mentioned, that connected the divide between operational tornado forecasting and tornado research.[1] This is not to diminish the analysis and forecasting techniques used in the 1950s by any means. On the contrary, the advancements in computer technology and radar would be virtually useless without the analysis techniques of the environmental parameters and conditions favorable for a tornadic storm.

So, what exactly are the basic atmospheric conditions which favor tornado development? The two primary types of parameters which are deemed significant for tornado detection and forecasting are the vertical wind profile and the potential buoyant energy of the air in the updraft entrainment layer.[2]

Within the vertical wind profile, parameters such as updraft rotation, shear-induced vertical pressure gradient, and storm inflow are the key wind-related ingredients for the development of supercells and supercell-induced tornadoes.[3] It is within this context that the term 'helicity' should be introduced. "Helicity has become an important parameter for evaluating the rotational potential of air in the storm inflow layer."[2] A storm is said to have high storm-relative helicity if "the local environment exhibits strong, storm-relative low-level winds which veer substantially with height."[4]

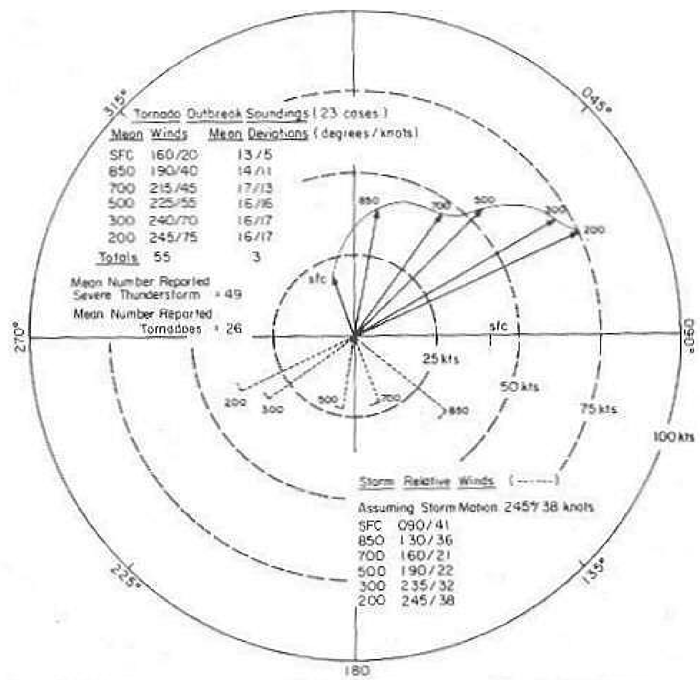

Fig. 3. Composite hodograph for 23 tornado outbreaks. Estimated storm-relative wind vectors are shown below the hodograph [from *Maddox*, 1976].

Maddox states that "storm-relative helicity is proportional to the area of the low-level wind hodograph that lies between the head of a storm motion vector and the environmental wind hodograph."[4] For relational value, a composite hodograph for 23 tornado outbreaks is given above. The estimated storm-relative wind vectors are shown below the hodograph.

This concept of using helicity is a relatively new method for determining the likelihood of tornado formation but has shown promise thus far in discriminating tornadoes from nontornadoes.[5] It is the helicity which induces rotation in the storm when "streamwise vorticity is ingested into the storm inflow layer and is tilted into the storm updraft."[3] Helicity is the modern term associated with the mean shear, which is used to assess the magnitude of the veering winds as greater heights are reached in the updraft. Doswell and Johns state that the "vertical wind shear structure is becoming the key factor in distinguishing tornadic from nontornadic events."[1] Helicity is a fairly recent and key tool in deciphering the vertical wind shear structure.

It is significant to remember also that <u>both</u> the lower and middle layers of the troposphere play a significant role in correct prediction of tornadic development. "From modeling results and observations, it appears that both (1) the wind profile in the low levels (i.e. the storm inflow layer) and (2) the strength of the wind field and shear extending through a deeper layer of the troposphere (i.e., through middle levels) are important to supercell-induced tornado development."[3] Low-level helicity can be present without the presence of deeper shear through the middle levels, so the presence of one of these factors does not imply the presence of the other.[3] This makes it necessary to examine both levels.

Yet vertical wind shear alone will not produce the tornadic development. The energy for a tornado must be put into the process. This is where the assessment of potential buoyant energy is critical. In other words, how much energy is available for entrainment into the updrafts of the storm? Traditional indices for static instability have been replaced by terms such as potential buoyant energy (PBE), which is also called the convective available potential energy (CAPE).[1] This is the " 'positive' area on a sounding associated with the buoyant part of a lifted parcel ascent between the level of free convection (LFC) and the equilibrium level."[1] This typically results from what in meteorology is called a "loaded gun sounding," where warm moist air lies underneath cool dry air. This *skew-T sounding profile* and its related information clearly depict the significance and relevance of a high CAPE value.

One might ask then what atmospheric conditions yield a high CAPE value. In short, the CAPE value will be high if there is deep moist convection involved. For example, the midwest and plains states of the United States will frequently exhibit high CAPE values on summer afternoons due to the warm moist air influx from the Gulf of Mexico. A good measure for the energy present in a storm can be calculated using the Bulk Richardson Number (BRN). It has been determined that the type of storm that develops is at least partially related to the BRN.[2] The BRN is defined[2] as:

$$BRN = \frac{B}{.5(U)^2}$$

where B = the CAPE for a lifted parcel in the storm's environment, and
U = a measure of the vertical wind shear through a relatively deep level (0-6 km above ground level).

"Results from numerical modeling experiments and a limited number of storm observations have suggested that growth of supercells is confined to values of BRN between 10 and 40."[2] The shortcoming of relying too heavily on the BRN alone is that this value is "a 'bulk' measure of the ambient shear and does not account for detailed aspects of the wind profile, particularly low-level curvature."[2]

Given the aforementioned conditions which make it favorable for tornadic development, it can be seen why conditions of strong shear with low-level southerly winds and a strong westerly jet at the upper levels are good bases for violent storms in the plains of the United States. Throw in a cold front and an upper-level trough and instability can be triggered to initiate violent weather, possibly even violent tornadoes. But it is important for the forecaster to "also address issues such as dynamic forcing and capping inversions to determine whether thunderstorms will develop in the first place. Because of these [environmental] factors one cannot produce a forecast concerning supercell-induced tornadoes from examination of wind parameters alone. However, it does appear that sufficient critical or 'optimum' values of the wind parameters must be present for thunderstorms to develop into supercells that produce tornadoes."[3]

Bearing this dynamic forcing variable in mind, along with the general atmospheric conditions necessary for tornadic storms, there are some "preferred" areas for tornadic storm development. "Under the proper dynamic forcing, tornadoes are spawned when squall line thunderstorms interact with an organized synoptic scale boundary, such as a warm front. Another favored region for tornado activity exists where a strong thunderstorm and a low-level boundary due to previous convective activity interact."[7] Another favored region for tomado activity is where an intense thunderstorm and an arc cloud interact.[7]

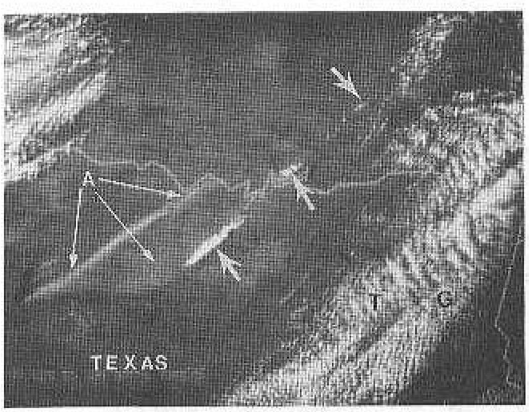

Fig. 3*a*. GOES-East 1-km resolution visible image at 1431 CST on March 11, 1988. Arrows point to initial cumulus formation in Oklahoma and north Texas where a squall line is beginning to form. Note the blowing smoke at A and the "rope" cumulus around Tyler (T) and Longview (G). *b*. GOES-East 1-km resolution visible image at 1731 CST on March 11, 1988. Arrows point to the squall line in eastern Oklahoma and Texas. Blowing smoke is still evident to the rear of the squall line, as is rope cumulus at Longview (G).

Fig. 3*b*. GOES-East 1-km resolution visible image at 1731 CST on March 11, 1988. Arrows point to the squall line in eastern Oklahoma and Texas. Blowing smoke is still evident to the rear of the squall line, as is rope cumulus at Longview (G).

Here are some examples of such favored regions.[7]

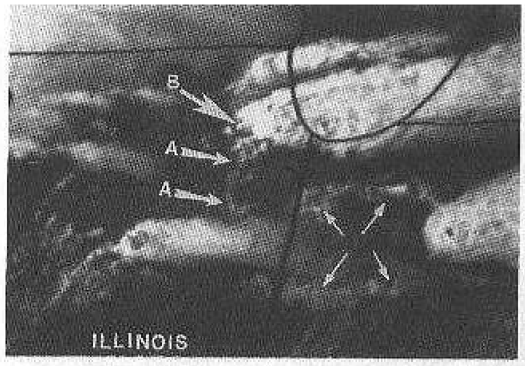

Fig. 7. GOES-East 1-km resolution visible image at 1645 CST on June 13, 1976. Arrows at A point to the "well-defined" arc cloud line south of Chicago. The thunderstorm at B is tornadic. Another set of arrows points to arc cloud lines in western Indiana; they are a product of the storm to their east.

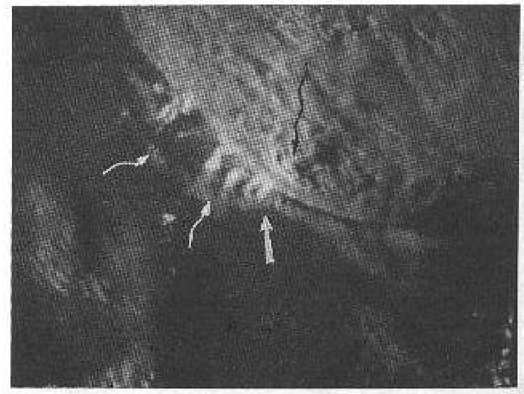

Fig. 8. GOES-West 1-km resolution visible image at 1816 CST on April 10, 1979. The view is into the back side of the Wichita Falls, Texas, tornadic storm. White wavy arrows point to the low-level arc cloud line, while the bold white arrow points to the location of the tower associated with the Wichita Falls tornado. The black wavy arrow points to the overshooting top above the tornadic region.

Along with the favored atmospheric conditions for tornado formation, the utility of radar has become an essential tenet in detecting and forecasting tornadic storms as well. There are some classic reflectivity signatures to aid in the detection and forecasting of such storms. They are "high reflectivity throughout the core of the storm, large reflectivity gradients, hook echoes, high echo tops, weak echo region, and large areal extent."[5] Just as each signature has proven to have utility in detecting tornadic storms, they do have their limitations as well. Discussion of certain radar signatures and certain limitations follows.

It was during the 1960s that Browning and Ludlam introduced the term "supercell" to describe the quasi steady state structure attained by some storms during their intense phases.[8] It is from these supercells that most, if not all, severe and violent tornadoes are produced.[8] "It is from the supercell that the "bounded weak echo region (BWER)" is often observed with the main storm updraft near the right rear flank of the supercell. Depending upon radar resolution and range, the BWER may not always be detected; however, the weak echo region (WER) is often more identifiable. Other equally important radar echo features associated with the supercell include (1) the highest storm top is positioned over the BWER (or WER) and (2) a notch of weaker echo surrounded by a hook (pendant) echo signifying the location of possible updraft rotation. Research efforts conducted during the 1970s have successfully identified the BWER as a center of significant updraft and cyclonic rotation."[8] "Browning found that the three-dimensional structure of the classic supercell was characterized with an extensive sloping overhang, a region of weak low-level reflectivity capped by the storm top (vault), and an intense hook-shaped echo surrounding the vault."[9] It is this same "vault" that is now known as the BWER.

You may have heard previously of the BWER, but you (if you've studied tornadoes at all previously) certainly have heard of the hook echo. A hook echo may help infer the existence of a mesocyclone in a storm.[9] The identification of mesocyclone, along with cell motion and wind profiling, are "the three pieces of radar information which support and are consistent with each other in providing credence for tornado potential."[5] The mesocyclone is a rotating updraft. The common occurrence of a mesocyclone and subsequent association as a precursor to tornadic development led to the undertaking of the Joint Doppler Operational Project (JDOP) during 1977-1979.[10] "The JDOP operation indicated that nearly all the storms with mesocyclone signatures produced surface damage, about one half of them produced tornadoes, and the existence of a mesocyclone signature permitted the lead time for tornado warnings to be increased by an average of 20 minutes."[10] It was findings such as these that helped lead to the procurement of a national network of Next Generation Weather Radars (NEXRAD) fully bringing Doppler capability to the forefront in tornado detection.[10] Yet a too heavily a reliance on mesocyclone identification for tornado prediction could be costly, even deadly.

"Not all mesocyclones produce tornadoes. In fact, the converse is true; most mesocyclones do not produce tornadoes."[11] Thus, the job of the forecaster then becomes to identify, then categorize a mesocyclone according to its tornado potential.[11] One method of doing so, which will not be discussed here, has been the calculation of excess rotational kinetic energy (ERKE), presented by Donaldson and Desrochers.[11] In recent years, because of its modest success in prediction of tornado formation, mesocyclone signatures have become the "most often used Doppler radar inputs to tornado warnings" by the National Weather Service.[11] However, along with the fact that the presence of a mesocyclone signature is indirect evidence of a tornado, there are other limitations to the reliance upon these signatures. "Because the Earth's curvature (horizon limitation) places the center of the lowest-elevation radar beam at greater than 4 km height when the range is 200 km (100 nm). No information is available on the low-level character of the mesocyclone, the important portion near the ground. Lastly, beam averaging will reduce the mesocyclone peak rotational velocity and, perhaps, cause underestimates of mesocyclone parameters."[11]

It is evident that even the most prominent of radar methods for tornado prediction is not without its limitations.

Returning to the hook echo and the indication of tornado development/occurrence with this signature, a few key points should be mentioned as well. Forbes, in 1981, “found a low probability of detection of a hook echo in a tornadic storm. Furthermore, the hook was absent three quarters of the lifetime of a tornadic storm and often made its first appearance after a tornado had already started.”[11] Thus, the prevalent idea that a hook echo is the main radar indication of tornado existence (i.e. detection) does significantly less to aid in the actual forecasting of a tornado event. To rely on the hook echo for forecasting could place many lives in peril through small lead times or missed events.[9]

From a thorough knowledge of the atmospheric conditions which make a storm favorable for tornado development to understanding the utility and limitations of both conventional and Doppler radars, several techniques and aspects have been covered which aid in the detection of tornado potential. The end goal is better tornado forecasting. As with any of the methods or parameters for prediction, reliance upon any of the means too heavily can prove costly. The most thorough and accurate forecasting of a tornado formation/event uses a combination of all available tools and means. “As recently as the 1980s, it has been suggested that most successful tornado warnings are still based on visual sightings, even when the warning message mentions radar signatures.”[11] Even (especially) the value of the storm spotter or weather observer cannot be replaced by advancing technology.

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